Catena 177 (2019) 70–83

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

The influence of landscape characteristics on the spatial variability of river temperatures

Antóin M. O'Sullivan[a,*], Kevin J. Devito[b], R. Allen Curry[a]

[a] Canadian Rivers Institute, Faculty of Forestry and Environmental Management and Biology Department, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada

[b] Department of Biological Sciences, CW 405, Biological Sciences Bldg., 11455 Saskatchewan Drive, University of Alberta, Edmonton, Alberta T6G 2E9, Canada

ARTICLE INFO

Keywords:
Geologic contacts
Geomorphology/physiography
River temperature
Surface-groundwater interactions
Thermal infrared imagery
Wetlands

ABSTRACT

River temperature is well established as an important variable for aquatic denizens. Given its importance, researchers are attempting to disentangle complex interactions between landscapes and river temperatures. We investigated how landscape variables of geomorphology, geology, and vegetation can explain a large portion of the spatial variations amongst tributary temperatures in the large, Miramichi watershed, New Brunswick. We utilize thermal infrared imagery (TIR) to characterize river temperature and remote sensed data to delineate landscape variables. Partial Least Squares regression (PLS) models indicated that variability in river temperature was associated with landscape attributes, but these differed with physiography. For the Clearwater Brook and Burnthill Brook watersheds located on the Miramichi Highlands physiographic unit, solar radiation exposure, surficial geology deposit (comprising gravels, sands, and minor silt), geological contact zones, and maximum watershed slope were strongly and positively correlated with river temperature. We stipulate that the interaction of slope steepness and geologic contact zones can produce complex local and larger groundwater interactions influencing river temperatures in this physiographic region. In the lower elevation, and lower relief, Cains River watershed, located on the Maritime Plains physiographic unit, watershed elevation and wetlands were significant and positively correlated with river temperatures. Here the main stem was cooler in the downstream reaches, likely due to the semi-confined channel interaction with groundwater discharge originating from the surficial deposits and fractured underlying sandstone of the lowlands, and possibly hyporheic processes. These findings illustrate how physiography and geomorphology influence thermal processes in flowing waters at both the landscape and local scales, and the resultant implications for management and conservation efforts both in terms of land use and climate change.

1. Introduction

Water temperature is one of the driving factors for biological processes in river ecosystems (McCullough et al., 2009; Isaak et al., 2017) and often defines critical habitats for biota (Curry and Noakes, 1995; Malcolm et al., 2004). Aquatic habitats are facing threats from human-altered landscapes including impacts on river thermal regimes (Steel et al., 2017), and the increasing air temperatures and changes in precipitation patterns with a warming climate (Koirala et al., 2014). For coldwater fishes in shallower rivers, warm summer temperatures increase physiological stress (Breau et al., 2011; Chadwick et al., 2015) and in response, individuals will relocate to colder river sections if such are accessible (Ebersole et al., 2003; Dugdale et al., 2016). These summer refugia can also provide winter refugia when warmer groundwater discharges to rivers (Cunjak, 1996; Linnansaari and Cunjak, 2010; French, 2014). These findings highlight the ecological importance of thermal refugia (Fullerton et al., 2018), especially for the survival of coldwater species during elevated temperature events in summer at least, and thus the need to develop a better understanding of watershed scale processes governing river temperature (Kurylyk et al., 2013; Isaak et al., 2015).

River flow and temperature regimes are a function myriad processes mostly governed by solar radiation, precipitation, and air temperature (Constantz, 1998; Soulsby et al., 2006), but modified by hydrogeology (Winter et al., 1998), geomorphology (Dugdale et al., 2015), and landscape features and changes (Tague and Grant, 2004; Detty and McGuire, 2010). Natural landscape scale processes can also affect river temperatures, e.g., wildfires (Isaak et al., 2009). Anthropogenic activities such as forest removal can also impact and alter surface and subsurface flows and effect river temperatures (Curry et al., 2002; Moore

* Corresponding author.
E-mail address: aosulliv@unb.ca (A.M. O'Sullivan).

https://doi.org/10.1016/j.catena.2019.02.006
Received 26 March 2018; Received in revised form 6 February 2019; Accepted 7 February 2019
Available online 14 February 2019
0341-8162/

et al., 2005). The magnitude and scale of how these processes influence river temperature is derived from the geomorphology, geology, and climate of a region (Tague et al., 2007; Caissie et al., 2007). A river's tributaries are typically smaller and often cooler than main stems (Goniea et al., 2006; Dugdale et al., 2015) because of smaller scale effects that can increase groundwater contributions to baseflow and where the interception of solar radiation by riparian canopy can be important (Caissie, 2006). Smaller river systems are also responsive to thermal fluxes due to hyporheic exchange (Hatch et al., 2006; Westhoff et al., 2011). The presence of lentic water bodies, such as ponds and wetlands, can increase river temperature via direct solar radiation on open, standing water (Majerova et al., 2015) or decrease temperatures via groundwater exchange (Weber et al., 2017).

Air temperature is traditionally used as an analogue for modelling of river temperature (e.g., Caissie et al., 2007), but it does not adequately predict the heterogeneity of river temperatures (e.g., Isaak et al., 2009). This is most problematic at finer reach scales where the patchiness of temperature patterns can be pronounced (Kurylyk et al., 2013; Wawrzyniak et al., 2016). Additionally, air temperature cannot account for subsurface advection processes that alter and modify the thermal properties of groundwater, which effects river temperature (Briggs et al., 2017; Johnson et al., 2017). Groundwater flow paths are complicated by the heterogeneous composition of surficial geology and bedrock leading to variability in recharge and discharge through space and time (Soulsby et al., 2006; Vidon and Smith, 2007). These geologic structures and associated processes can influence river flow and thermal regimes (Constantz, 1998; Larocque et al., 2010), which in turn affect biological processes (McCullough et al., 2009; Fuhrman et al., 2018). However, researchers are just beginning to address these complexities across broader scales (Torgersen et al., 1999), such as the influence of valley morphology and river sinuosity (Dugdale et al., 2015), and geology (Briggs and Hare, 2018) on river temperature regimes. Landscape frameworks acknowledging surficial geology and bedrock geology (Winter, 2001; Devito et al., 2005) can be used to develop a more robust, conceptual understanding of hydrologic regimes at intra- and inter-watershed scales. These become especially important for understanding the impact of warming climate scenarios where high frequency, high magnitude weather events push flows and temperatures to extreme highs and lows in running waters (Warren et al., 2011; van Vliet et al., 2013).

Until recently, analyzing the increasingly complex data sets describing spatial and temporal thermal structure of flowing waters has been beyond computing and programming abilities. Contemporaneous advancements in technologies such as Geographical Information Systems (GIS), Light detection radar (LiDAR), and thermal infrared imagery (TIR), and the development and application of robust multivariate statistical methods such as Partial Least Squared Regression (PLS – Wold et al., 1984) and Spatial Statistical River Network models (Ver Hoef and Peterson, 2010) are allowing researchers to disentangle these complexities across scales. The result is an improvement of our understanding of a river's thermal regime and its control of the biological components of the ecosystem (e.g., Petty et al., 2014; Steel et al., 2017), and the consolidation of associations amongst landscape variables across fine to coarse scales (e.g., Hrachowitz et al., 2010; Monk et al., 2013).

Studies are emerging that identify summer coldwater patches and the link to geomorphic features (Dugdale et al., 2015; Wawrzyniak et al., 2016). A next step is the investigation of the effects of physiography and geology at a range of scales on river temperature (Curry and Devito, 1996; Briggs et al., 2017). Hydrogeologic studies have established the effect of geological structure on groundwater discharge regimes (James et al., 2000; Briggs et al., 2018). Acknowledging the interconnectedness between the riverscape and the landscape (Hynes, 1975), we undertake an interdisciplinary study across hydrology, hydrogeology, forestry, geology, and geomorphology to examine the potential influence of landscape-to-reach scale variables on the spatial variability of surface water temperatures in a river network. In this study, we examine watershed scale, surface water temperatures in the Miramichi River, New Brunswick, Canada which is a large system spanning multiple geomorphologies (the surface features), physiographic zones (geology and its evolution), and vegetation cover, and which supports intensive forest harvesting. We extend upon studies by Monk et al. (2013) by comparing most probable landscape variables influencing river temperature in three watersheds in two physiographic units. By continuing to incorporate more components at the scale of the hydrological landscape, e.g., adding physiography and geology to define fine scale hydrological units (HUs) that overlay broader, hydrological response areas (HRA; Devito et al., 2017) of the complete hydraulic system (Winter, 2001), our goal is to improve models that identify the regulating components of a river's temperature and simultaneously improve decision-making tools for managing land use and adapt to climate change to protect river ecosystems (Steel et al., 2017; Johnson et al., 2017).

2. Methods

2.1. Study area

New Brunswick lies in the Atlantic Maritimes Ecozone. It includes the Canadian Appalachians underlain by three tectonostratigraphic zones (Williams, 1979). The region's geological constituents are Pennsylvanian, Silurian, Ordovician, and Mississippian, and it experienced Quaternary glaciation, isostatic depression and rebound, and submergence and emergence (Rampton et al., 1984). The surficial geology is comprised of ablation and lodgment till, and associated sand and gravel deposited by Late Wisconsinian ice or with minor reworking by water (Rampton et al., 1984).

The Miramichi River Watershed drains an area $\approx$14,000 km^2 and encompasses two major physiographic units in New Brunswick - the Miramichi Highlands and the New Brunswick Lowlands (Maritime Plains), and (Fig. 1). During the late Wisconsin glaciation, the entire watershed was covered with glacial ice (e.g., Curry, 2007), which advanced from the west and north creating hills from the Appalachian Mountains (Cunjak and Newbury, 2005). Following isostatic rebound and glacial retreat, meltwaters incised large meandering valleys into the landscape creating terraces and alluvium deposits commonly underlain by glaciofluvial, lacustrine and marine deposits (Rampton et al., 1984; Cunjak and Newbury, 2005). Groundwater discharge to streams and rivers is common (Monk et al., 2013; Kurylyk et al., 2014). Ninety percent of the watershed is covered by forest comprised mainly of softwoods with mixed hardwoods (Cunjak and Newbury, 2005). The dominant land use within the watershed is forestry and that includes a high density of roads.

TIR data was collected for Burnthill Brook and the Cains River on the 23rd of July 2008, whilst the Clearwater Brook TIR dataset was acquired during 29th of July 2009. The accumulative precipitation (rain) in the Clearwater Brook and Burnthill Brook watershed's (http://www1.gnb.ca/0079/FireWeather/FireWeatherHourly-e.asp?stn=Clearwater), between March to July 2008 was 359 mm, and between March to July 2009 was 579 mm, whilst the Cains River (Bantalor Meteorological Station, http://www1.gnb.ca/0079/FireWeather/FireWeatherHourly-e.asp?stn=Bantalor) experienced 389 mm rainfall between March to July 2008 (Table 1). The climate characteristics of the area are presented in Table 2.

Clearwater Brook and Burnthill Brook are 5th order rivers draining an area about 325 km^2 and 290 km^2, respectively, and headwaters in the Miramichi Highlands (Fig. 1(b)). Both watersheds have similar bedrock geology and surficial geology, but differ in spatial distribution (Table 1). The watersheds are underlain by deep water clastic, mafic and felsic rock containing contact zones and faults throughout from tectontic movement and orogenic processes (Rampton et al., 1984). The age of lithologies in this region ranges from Cambrian to Late Devonian

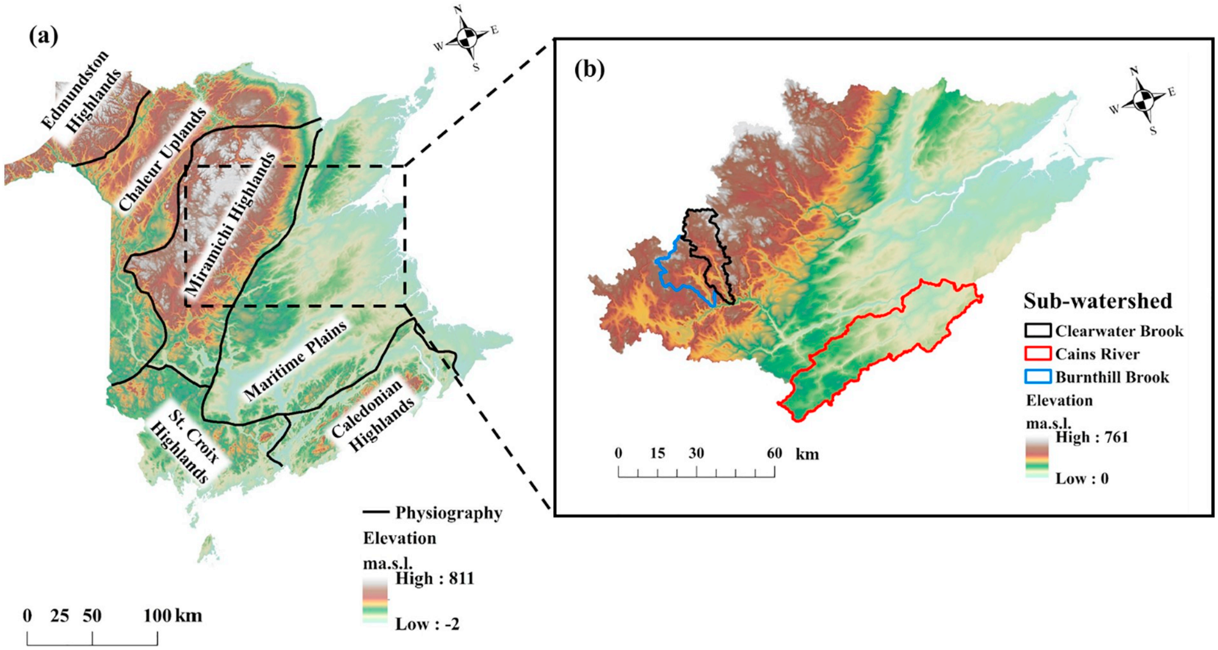


Fig. 1. (a) Topography and physiographic units of New Brunswick, and (b) topography of the Miramichi watershed, where the Cains River watershed is contained within the Maritime Plains physiographic unit, and the Clearwater Brook and Burnthill Brook watersheds lie within the Miramichi Highlands physiographic unit.

(540–359 million years ago (Mya)), where older rocks are more fractured and weathered than younger rocks (Rampton et al., 1984). The surficial geology comprises Late Wisconsinan (50,000 years before present (YBP)) loamy lodgment till, minor ablation till, hummocky, ribbed and rolling ablation moraines along with Wisconsinan sand, gravels and minor silts (Rampton et al., 1984). The Cains River is a 5th order river with a watershed about 1400 km^2. It is the only major tributary of the Miramichi River located entirely within the Maritime Plains of the New Brunswick lowlands physiographic unit (Fig. 1(b); Table 1). The Cains is underlain by fluviatile conglomerate and fractured sandstone sequences ranging from the Late Devonian to Carboniferous (372.2–299 Mya) (Rampton et al., 1984). The watershed is blanketed with Late Wisconsinan sandy till in the upper watershed, and Wisconsinan sand, gravels and silts in the lower watershed. There are bogs, fens, and swamps throughout, with the majority occurring in uplands areas (e.g. Rampton et al., 1984).

2.2. Geospatial data

TIR data (wavelength band: 8–9.5 μm) was collected by Quantum Spatial using a thermal camera (FLIR Systems SC3000 LWIR) mounted to a gyro-stabilized unit on the underside of a helicopter (Monk et al., 2013). Approximately 30 km's of Burnthill Brook were surveyed, and ≈52 km's of the Cains River were surveyed in 2008, whilst ≈45 km of Clearwater Brook were surveyed in 2009. Flight paths were flown longitudinal to the river channel, with the camera pointing towards nadir. The flight altitude was chosen to optimise resolution whilst providing a ground footprint that encompassed both the active channel and immediate floodplain. In-river thermographs (Onset, Hobo UA-002-64, pendant temperature loggers – accuracy 0.5 °C, housed in a white uPVC casing to shield solar radiation) were deployed throughout study areas, collecting data at 10-min intervals, for calibration and verification of TIR accuracy (n = 3 for the Cains – located at 52, 83, and 103 km upstream of the mouth, n = 2 for Burnthill Brook – located at 3.5 and 12 km upstream of the mouth, and n = 2 for Clearwater Brook – located at 10 km, and 25 km upstream of the mouth;). The Cains TIR computed radiant temperatures showed agreeance with in-river thermographs (error of ± 0.1 °C). However, the furthest downstream thermograph displayed a discrepancy of 1.9 °C. Upon inspection of the thermograph and TIR imagery, no source of error could be found. Quantum Spatial (unpublished report) suggest variable weather conditions during the Cains River acquisition, and especially near the downstream reaches, may have contributed to the observed difference. It should be noted that the in-river thermographs were not calibrated prior to deployment, e.g., immersion in an ice bath. Therefore, it is possible the noted discrepancy between the computed radiant temperatures and the in-river thermograph, may be due to inherent inaccuracies in the thermograph itself, or a combination of both weather conditions, and thermographs errors. There was a discrepancy of ± 0.1 °C between TIR and river-based loggers for the Burnthill Brook. There was a divergence of −0.2 to 0.1 °C between TIR and river loggers for Clearwater Brook. Images were collected every second, resulting in an image overlap of 40–70% (all flights). Individual frames were then manually geo-rectified by finding a minimum of 6 common ground control points (GCPs) between the image frames and the 1-m Softcopy Ortho-photomap Data Base (SODB) imagery downloaded from GeoNB (Quantum Spatial, unpublished data). The resultant TIR images had a pixel resolution of 60 cm.

To model temperature, we selected a subset of tributary watersheds within each main watershed, which were determined by the ability to detect water temperature at the mouth, e.g., limitations based on the TIR acquired data. These tributary watersheds ranged in size from 2 to 96 km^2. At the confluence with the main river, but still within the tributary itself, water temperatures were quantified by querying pixel values (temperature) from the centre of the tributary channel and averaging the value of a 9-point sample to a GIS database (Quantum Spatial, unpublished data). Temperatures were only sampled along what appeared to be, via inspection of 1 m resolution aerial imagery and 60 cm resolution TIR imagery, surface water flow. Upstream sample distance was dependent on where the major temperature differential was noted between the tributary and main stem. Wilbur (2012) demonstrated that the studied reaches were well-mixed and the likelihood of thermal stratification was low, i.e., the TIR extracted temperatures represent the complete water column in these systems. The dependent variable for the temperature models was the tributary's median temperature and the final number of tributary watershed sampled were: n = 8 for Burnthill Brook; n = 14 for Clearwater Brook; and n = 13 for Cains River (Fig. 2).

Table 1
Physical characteristics and total precipitation and mean air temperature prior to the TIR measurements for the Cains River and Burnthill Brook watersheds (March to July 2008), and for the Clearwater Brook watershed (March to July 2009). A single meteorological station borders Burnthill and Clearwater Brook watersheds (Energy and Resource Development, 2016).

Watershed	Watershed area (km^2)	Geology	Surficial geology	Watershed mean slope (degrees)	River mean slope (degrees)	% of watershed harvested[a]	March–July total precipitation (mm)	March–July range and average air temperature (°C)
Clearwater Brook	324	Deep water clastic Felsic intrusion Mafic intrusion Felsic intrusion	*Glaciofluvial sediments:* Sands, gravels, minor silt *Morainal sediments:* Loamy lodgment till, minor ablation till, silt, sand, rubble	6.4	3.2	8.6	(2008) 359 (2009) 579	−22.0–30.1, 7.7 −20.5–30.6, 7.8
Burnthill Brook	289	Deep water clastic Felsic intrusion Mafic intrusion Felsic intrusion	*Glaciofluvial sediments:* Sands, gravels, minor silt *Morainal sediments:* Loamy lodgment till, minor ablation till, silt, sand, rubble	5.7	2.3	4.2	(2008) 359	−22.0–30.1, 7.7
Cains River	1400	Terrestrial sediments	*Organic sediments:* Bogs, fens, swamps, peat, minor silt, and fine sand *Morainal sediments:* Mainly, stony and sandy	1.6	3.2	11.7	(2008) 389	−27.0–31.2, 8.7

[a] Harvest occurred within the 7 years prior to TIR acquisition.

To investigate the spatial variability of each rivers' longitudinal temperature profile (LTP), the median temperature for each sample image was determined. Similar to the tributary analysis, temperatures were only sampled along what appeared to be, via aerial image and TIR inspection, the main flow channel in the river. This resulted in n = 431 median river temperature measurements for Clearwater Brook, n = 392 for Burnthill Brook, and n = 631 for the Cains River.

Remotely sensed data were utilised to delineate model descriptors (the independent variables), e.g., fluvial geomorphologic features, terrestrial geomorphologic features, and forest inventory data. Watershed drainages and river networks were delineated from a 10 m digital elevation model (DEM), resampled from a 30 m DEM, and derived using ESRI's Arc Hydro toolset. To define artificial river networks, the 10 m DEM was reconditioned with a suite of National Hydro Network (NHN) data (the Canadian inland surface waters GeoBase https://open.canada.ca/data/dataset/a4b190fe-e090-4e6d-881e-b87956c07977). Reconditioning involves adjusting the DEM by 'burning' the vector layer into the raster DEM. This reconditioning helps mitigate any errors which may be inherent in the DEM by imposing NHN river networks on the DEM (Li, 2014). Once reconditioned, a 1 km^2 flow accumulation area was applied to initiate a river (ESRI, 2018). Watershed and river slopes were derived from the 10 m DEM using the Slope function in ArcMap (ESRI, 2018) – where a slope value for each 10 m pixel was calculated. Geomorphic characteristics were computed using ArcMap (ESRI) zonal statistics and derived from the 10 m DEM, where minimum, maximum, and average of raster data, such as elevation or slope, are computed for an area of interest (Table 2). For instance, we characterize watershed slope by minimum, maximum, range, and average slope within the watershed of interest. We use the same method to calculate watershed elevation, aspect, solar radiation (see below), and river slope metrics.

A solar radiation exposure model for each watershed was built using ESRI's ArcGIS Area Solar Radiation tool, again using the 10 m re-sampled DEM (Table 2). The 10 m DEM was masked with the river network to produce a 10 m pixel size raster. This new river network raster was then utilised to develop the solar radiation model. The solar radiation analysis tool calculates insolation across a landscape based on methods from the hemispherical viewshed algorithm developed by Fu and Rich (2002). The tool was set to collect total solar insolation on the day of TIR acquisition from 08:00–17:00, replicating solar azimuth and altitude on the day of TIR acquisition (Wh/m^2).

Wetlands (measured in km^2) were delineated by visual inspection of aerial imagery and sourced from GeoNB (http://www.snb.ca/geonb1/e/index-E.asp). River length migrating through wetlands was calculated by clipping the length of river network overlaying the wetland polygon (measured as km). Lentic bodies (km^2) were also extracted from the GeoNB data sets. Sinuosity and gradient were derived from the DEM using Dilts (2015) Stream Gradient and Sinuosity Toolbox (SGT) for ArcGIS (https://www.arcgis.com/home/item.html?id=c8eb4ce1384e45258ccb-a1b33cd4e3cb). The method involves dividing the river network into 200 m river segments based on the spatial distribution of meanders, and then gradient and sinuosity for each segment was calculated both for the artificially derived river network and the DEM it was built from. Watershed total river gradient was measured in degrees (°) and total watercourse sinuosity was calculated as the ratio of river-line length to straight line length, where 1 is a straight river section and values > 1 indicate greater sinuosity (dimensionless). Zonal statistics were calculated for both gradient and sinuosity to obtain average river gradient and sinuosity upstream of the sampled TIR point.

We used provincial datasets (http://www.snb.ca/geonb1/e/DC/catalogue-E.asp) to examine and define the area's geologic composition. Amongst the three watersheds, there were seven bedrock geologies units (n = 7), nine surficial geology units (n = 9), and twenty-three soil units (n = 23; Table 2). Surficial geology and soil type were delineated as the total area (km^2) of the watershed. Bedrock geology was measured in km^2. Faults and geological contacts were quantified by

Table 2
Landscape characteristics of the tributary watersheds representing the dependent variables in the tributary river temperature prediction models. For bedrock geology, surficial geology, and soil classes, n $_{total}$ is the total number of classes – accumulated across all study sites. Lentic Waterbodies represent lakes, small ponds, and beaver ponds.

Landscape characteristic	Landscape descriptor	Metric	Data layer	Data source
Fluvial geomorphology	Sinuosity	Non-dimensional	Digital elevation model (resampled to 10 m, from 30 m)	NASA Shuttle Radar Topography Mission (SRTM)
	Gradient	Degrees (°)`		
	Elevation	Meters (m)		
	Solar radiation	WH/m^2		
	Aspect	Degrees (°)		
	River order	Strahler		
Terrestrial geomorphology	Watershed slope	Degrees (°)	Digital elevation model (resampled to 10 m, from 30 m)	NASA Shuttle Radar Topography Mission (SRTM)
	Watershed elevation	Meters (m)		
	Aspect	Degrees (°)		
	Watershed drainage area	km^2		
Hydrography	Wetlands	km^2	New Brunswick Hydrographic Network	GeoNB
	Lentic Waterbodies	km^2		
	Peatlands	km^2		
Geology	Bedrock ($\mathbf{n_{total}}$ = 7)	km^2	Geological map	GeoNB
	Surficial ($\mathbf{n_{total}}$ = 9)	km^2		
	Soil ($\mathbf{n_{total}}$ = 23)	km^2		
	Contact zones	km		
	Fault lines	km		
Forest	Harvest	km^2	Forest inventory	Department of Natural Resources (NB)

their length (km) passing through the watershed. The spread of geologic data, and therefore the range of geologic variables, differed across our 3 study sites due to spatially dissimilar depositional modes.

Forest harvest data was obtained from the provincial dataset (http://www.snb.ca/geonb1/e/DC/catalogue-E.asp). The state of forestry activity in a watershed was assessed based on the forestry applications in the seven (7) years prior to TIR acquisition in 2008/9 (measured in km^2 harvested with no differentiation of harvest type; Table 1). We used this time period because Alexander (2006) demonstrated that groundwater temperatures within a clear-cut with a buffer zone > 15 m returned to pre-cut conditions after 7–8 years in the Little Southwest Miramichi watershed.

2.3. Statistical analysis

Partial Least Square Regression (PLS) was selected for modelling because of its ability to handle challenges of smaller data sets, i.e., overfitting models, with highly correlated predictor parameters (e.g., Carrascal et al., 2009). PLS combines features from Principal Component Analysis (PCA) and multiple linear regression (MLR) to predict **Y** (an observation) from **X** (a descriptor) (Abdi, 2010), i.e., we predict the median river temperature of a tributary using landscape parameters from its watershed (see Table 2). PLS searches for a set of components (or *latent vectors*) that performs a simultaneous decomposition of **X** and **Y** applying the constraint that these latent vectors explain as much of the covariance between **X** and **Y** as possible (after Abdi, 2010; Eriksson et al., 1995). Monk et al. (2013) highlight that multicollinearity issues that are common in environmental data are overcome by reducing descriptors to latent vectors. Resampling was performed to reduce the bias of estimators and evaluate the estimator's variance. A jackknife technique was chosen over bootstrapping, again owing to the size of the sample size (Chin, 1998). Jackknifing involves iteratively subsampling according to an ascribed deletion number, where *n* samples are deleted. Pseudo-jackknife values (J_i) are calculated for each *n* subsample (see Chin, 1998). Then, the mean of these pseudovalues is calculated along with standard deviation and standard error. Finally, a t-statistic with n – 1 degrees of freedom is used to test if the original samples differs from the subsample.

An excellent overview of both PLS and jackknifing techniques is given in Chin (1998). In our analysis ≈21–25% of the observations in each tributary watershed model were randomly selected and the jackknife technique was applied (i.e., n = 2 (25% of total observations) for Burnthill Brook; n = 3 (21% of total observations for Clearwater Brook; and n = 3 (23% of total observations) for the Cains River)).

PLS performance is explained by the metrics Q_y^2, R_x^2 and R_y^2, referring to a measure of global contribution of the components to the predictive quality of the model, a measure of the explanatory power of the components for the dependent variables of the model, and a

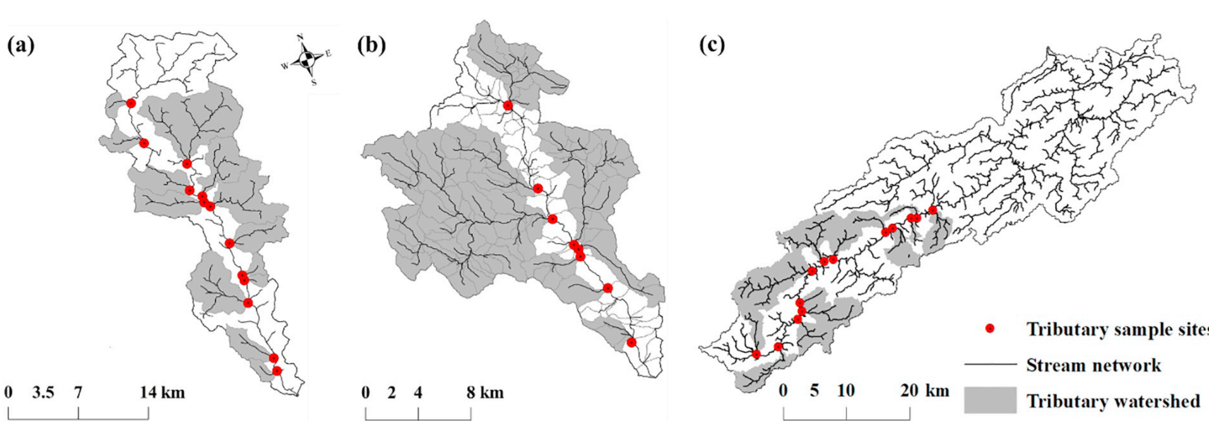


Fig. 2. Delineation of tributary watershed for (a) Clearwater Brook (n = 13); (b) Burnthill Brook (n = 8); and (c) Cains (n = 14) watersheds, along with tributary temperature samples sites.

measure of the explanatory power of the components for the explanatory variables of the model, respectively. Sharma and Kim (2012) used a Monte Carlo simulation to compare common PLS indices (coefficient of determination (R^2) and goodness of fit (GoF), Q_y^2), in selecting the best model and under differing conditions, e.g., sample size, data distribution. Their results showed that utilisation of R^2 and GoF criteria may lead to the selection of highly fitting models, but ones which are unnecessarily complex. They concluded by recommending strongly the use of Q_y^2 - which emerged as an equally good selection criterion as Akaike information criterion, (AICu), and Bayesian information criterion (BIC). We qualify model selection using both the more commonly found R_x^2 and Q_y^2. Q_y^2 is set equal to $(1–0.95^2) = 0.0975$, where a latent vector is kept if its $Q_y^2 \geq 0.0975$, corresponding to $p < 0.05$, (e.g. Eriksson et al., 1995; Wold et al., 2001, and Abdi, 2010).

PLS also utilizes Variables Importance for the Projection (VIP) that measure the importance of an explanatory variable for the building of components. Eriksson et al. (1995) proposed that highly influential variables are VIP > 1 and moderately influential variables have a VIP > 0.7. Our initial set of potential explanatory variables (where n is dependent on the watershed; see Table 2) was reduced by iteratively (minimum 10 iterations) removing variables with p > 0.05, and then re-running until only significant variables are remaining. We created a PLS model with 1 or 2 latent vectors for each of the watersheds. Data preparation was conducted in Microsoft Excel, and statistical analyses were run in XLStat – Base (XLStat, 2016).

3. Results

3.1. Burnthill Brook

3.1.1. River Temperature Model

The development and extraction of landscape variables for the Burnthill Brook tributary temperature median model resulted in a total of $n = 49$ descriptor variables for analysis. The penultimate tributary median temperature model contained one latent vector and produced a $Q_y^2 = 0.635$, $R_x^2 = 0.59$, and $R_y^2 = 0.812$. The addition of a second orthogonal latent vector increased Q_y^2 to 0.703, R_x^2 to 0.869, and R_y^2 to 0.86. The final model's root-mean-square-error (RMSE) was 0.301 °C, and the mean-square-error (MSE) was 0.091 °C. Four influential parameters for the tributary's median river temperature were identified and all parameters were positively correlated with river temperature (Fig. 3). The mean river solar radiation and watershed maximum slope were predicted to be highly influential (VIP > 1.0), whilst lentic water bodies and geological contact zones were significant (VIP > 0.7).

3.1.2. Longitudinal Temperature Profile

The main stem, Longitudinal Temperature Profile (LTP) for Burnthill Brook was moderately spatially heterogeneous, with surface temperatures ranging from 15.4 to 17.8 °C over ≈30 km (Fig. 4). However, the variability in surface temperatures in the upper reach was as great as, or greater than variability over the entire main stem of the river. A total of 57 inflow seeps, springs, side channels, and unnamed tributaries – the majority of these were not included in the tributary PLS analyses due to DEM resolution - were sampled along the main stem of Burnthill Brook (Fig. 4). Assuming a linear relationship between temperature and distance downstream for simplicity, the inflows displayed a general positive trend in temperature in the downstream direction ($r = 0.03$; $p < 0.05$) (Fig. 4(a)). The majority of these inflows (41 of 57) occurred within 15 km of the headwaters. The coolest inflow was 10.5 °C and occurred ≈1.25 km downstream of km 0 (headwaters), whilst the warmest inflow was 18.6 °C and occurred ≈4.2 km downstream from the headwater (Fig. 4(a)). The inflow of the South Branch of Burnthill Brook dropped the surface temperature of the main stem river from 16.2 to 15.4 °C (km 14.3). Three warming reaches were observed at km 0.25, 1.1, and 2.5 and co-occurring with upland lentic bodies – we expand upon this in the Discussion section.

3.2. Clearwater Brook

3.2.1. River Temperature Model

The extraction of landscape descriptors for the Clearwater Brook model predicting median tributary river temperatures resulted in $n = 51$ variables for the PLS analysis. The final model for Clearwater Brook median tributary temperatures identified six influential variables (Fig. 5), all of which were positively correlated with river temperature. The model contained two latent vectors and produced a $Q_y^2 = 0.843$, $R_x^2 = 0.718$, and $R_y^2 = 0.955$. The model RMSE = 0.286 °C and MSE was 0.082 °C. The maximum river solar radiation, the occurrence of a glaciofluvial deposit (GP3) generally > 1.5 m thick (comprising gravels, sands, and silts), and the watershed's maximum slope were highly influential VIPs. The spatial arrangement of these highly influential variables is displayed in Figs. 6 and 7. Interestingly, named tributaries with the largest areas of the GP3 deposit, also have the highest levels of solar radiation amongst examined tributaries (see Fig. 7). Lentic bodies, geological contacts, and current harvest were moderately influential VIPs. The least significant variable was sinuosity, and had a negative correlation with median tributary temperature.

3.2.2. Longitudinal Temperature Profile

The LTP for the main stem of Clearwater Brook displayed spatial heterogeneity and a warming trend with downstream distance (Fig. 7). The coolest reach of the main stem occurred in the headwaters (18.8 °C), whilst the warmest reach occurred ≈35 km downstream (21.1 °C). In addition, 3 warming reaches were observed at km 4.9–7.5, 11.5–13 and 27.5–34.5 (Fig. 7(a)). 69 inflows to the main stem were sampled (including seeps, springs, side channels, and unnamed tributaries) and ranged from 13.2 to 20.8 °C (Fig. 7). Similar to the main stem, the temperatures of the smaller inflows displayed a general positive trend in the downstream direction ($r = 0.02$; $p < 0.05$). Further, a trend of increasing watershed slope – in both the main stem and tributaries – for the lower section of the watershed co-occurs with an increase in water temperatures (see Fig. 7(b)). Additionally, an increase in river temperature (≈2.5 °C over a ≈4.8 km reach between ≈28.5–35.3 km) occurs in the lower section of the watershed and overlays a bedrock geological contact (Fig. 8).

3.3. Cains River

3.3.1. River Temperature Model

The extraction of landscape data for the Cains watershed tributary median temperature model lead to $n = 43$ landscape descriptors for the analysis. The final model for the Cains Watershed had one latent vector, and identified four influential variables for the tributary's river temperature (Fig. 9). The models produced a $Q_y^2 = 0.787$, $R_x^2 = 0.674$, and $R_y^2 = 0.830$, with a model RMSE of 0.752 °C and MSE of 0.565 °C. All VIP's were positively correlated with river temperature, except for mean river slope, which was negatively correlated. VIPs > 1 predicted to be highly influential were 'Maximum Elev' = the maximum watershed elevation in the sampled tributary; '% thru WL' = the length of river running through a wetland complex, and 'Wetlands' = area of wetlands upstream of the observed temperature point, whilst 'Stream Slope' = the mean river slope in the sampled tributary, had a 1 < VIP > 0.7.

3.3.2. Longitudinal Temperature Profile

The LTP for the Cains River displayed spatial heterogeneity with temperature ranging from 18.6 to 20.8 °C over ≈52 km. In contrast to the Highland watersheds, the coolest reach of the main stem occurred farthest downstream at 52 km from the headwaters (Fig. 10). The warmer surface temperatures observed in the upper reaches of the main stem were associated with larger percent coverage of wetland and

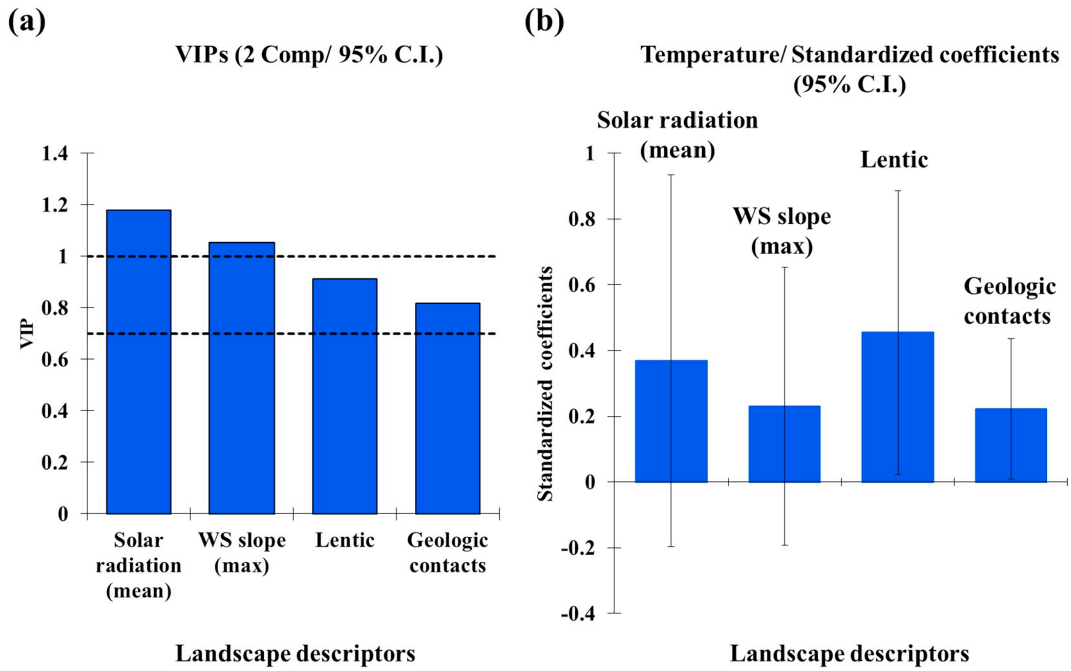


Fig. 3. (a) Variables of Importance (VIPs) and (b) standardized coefficients (± 95% C.I.) for a Partial Least Squares (PLS) model with two latent vectors predicting tributary median surface water temperature with in the Burnthill Brook watershed. Where 'Solar Radiation (mean)' is the mean calculated solar radiation value (Wh/ m^2) for each tributary, 'WS Slope (max)' is the maximum watershed slope calculated for each tributary watershed, Lentic refers to lentic water bodies (lakes and pinds), and, 'Geological Contacts' are contact zones between differing bedrock lithologies.

wetlands adjacent river. Similar to the main stem temperatures, the 99 inflows (ranging from 9.6 to 20.6 °C) entering the main stem displayed a general negative trend in temperatures moving downstream ($r = 0.134$; $p < 0.05$).

4. Discussion

We assessed probable landscape variables for their potential as predictors of surface water temperatures for headwater tributaries in the Miramichi River, NB, Canada. The variables, or characteristics, identified as significant for river temperatures were solar radiation, lentic and wetland water bodies, relief (slope), with suggestions of influence by overburden coarseness, bedrock permeability, and channel configuration in the landscape. These characteristics show similarities to land surface form and geologic frameworks used to conceive generalized hydrologic landscapes in other geographic regions and climates (Winter, 2001; Cowood et al., 2017). Further, these characteristics can be utilised to define finer scale hydrological units (HUs), such as areas of unique slope, soil, and vegetation, that overly larger, hydrological response areas (HRA), defined by depth and texture of the geologic substrate to describe variations in surface and subsurface storage, transmissivity, and scale of flow path, for this region - similar to that proposed by Devito et al. (2017). In our study the Highland and Lowland physiographic units define regions that vary in the proportion and configuration of landscape characteristics (HUs and HRAs). The use of such HUs and HRAs within the context of larger regional physiographic units and climate can help in understanding regional differences in water movement and aid in better management of water resources.

Our analysis indicated 45 characteristics were not significant for Burnthill Brook median tributary temperatures; 44 characteristics were not significant for Clearwater Brook tributaries, and 39 characteristics were not significant in the Cains River tributaries. The role of these characteristics influence on river temperature in general cannot be fully assessed without increased synoptic surveys of more tributary catchments that expand the range in landscape characteristics and potential HUs and HRAs to investigate the effects represented by each characteristic through both space and time. 11 of the characteristics generated significant VIPs for the models predicting river temperatures and likely indicates the dominance of certain surface landforms and geology and their roles of influencing river temperatures in general within these two regional physiographic settings. These are discussed in the context of potential HUs and HRAs in these two physiographic regions.

4.1. Miramichi Highland watersheds

In both watersheds, solar radiation was a significant positive variable (VIP > 1) in the model projections of river temperatures. This response is predicted because, as Caissie (2006) describes, heat flux at the air-surface interface is a result of energy exchange mainly through solar radiation or net short-wave radiation, net long-wave radiation, evaporative heat flux (evaporation), and convective heat transfer. The solar energy control of a river's surface water temperatures is fundamental, but there are additional landscape-scale characteristics in the matrix of factors that control river temperatures (e.g., Johnson, 2004; Garner et al., 2017; and Wawrzyniak et al., 2017).

An additional landscape characteristic of significance for predicting temperatures in the highland tributaries was watershed slope, which was positively correlated with river temperature. The steepest sections, and tributaries, of both studied watersheds occur in their lower reaches (see Figs. 4 and 7). In these sections, it is probable that shallow surficial deposits exist, owing to their geomechanical composition and the reposing angle of the slope (Rampton et al., 1984). These shallow surficial deposits have less storage potential (Winter et al., 1998) and potentially creates near surface flow paths (Dunne and Leopold, 1978). Shallow flow paths inherently lead to water which is closer to the surface, and will be more susceptible to fluxes in surface air temperature – where warming in the summer, or cooling in the winter (Kurylyk et al., 2014; Briggs et al., 2017). This can be exasperated during drought conditions when shallow groundwater can disconnect from the river and surface water sources (Devito et al., 1996), thus, leading to river temperature increases.

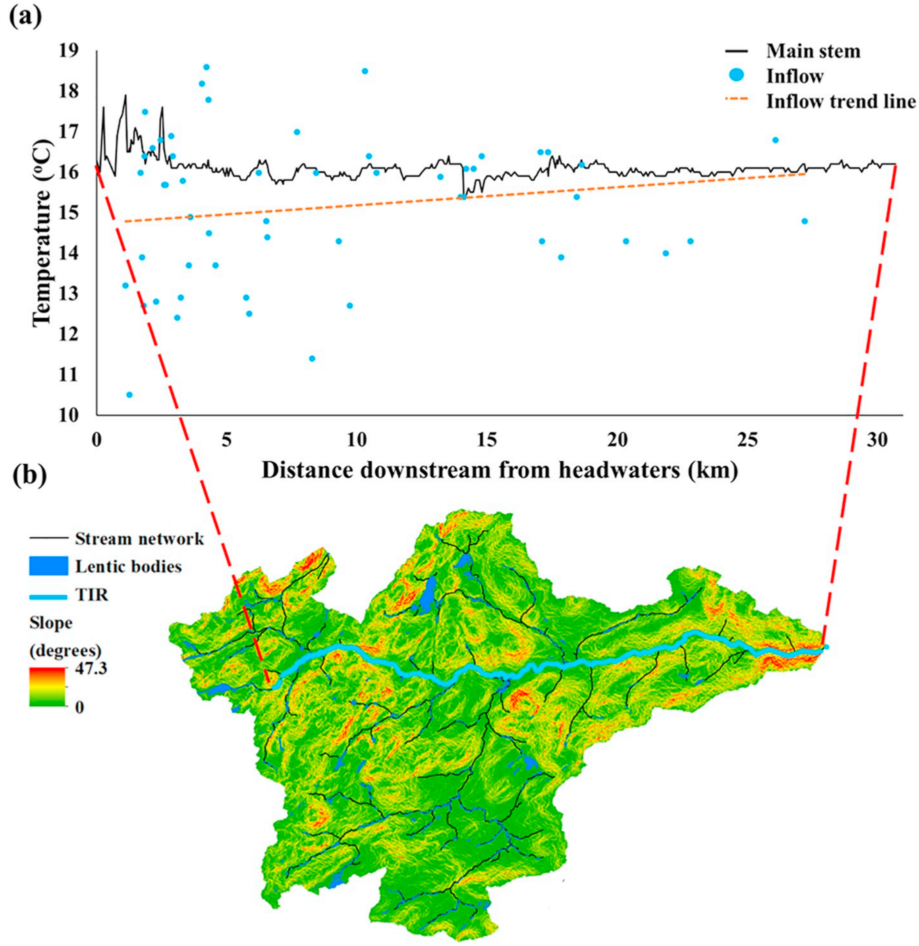


Fig. 4. (a) Burnthill Brook Longitudinal Temperature Profile (LTP) where km 0 identifies the headwater reaches, and moving downstream and three warming reaches are identified between km 0.2–3.3. The black line denotes the main stem temperature profile, the blue dots indicates inflows, and the orange dashed line is the inflows trend line. (b) The spatial extent of TIR data and Burnthill stream network and lentic bodies (in blue) imposed on the watershed slope of the Burnthill Brook. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

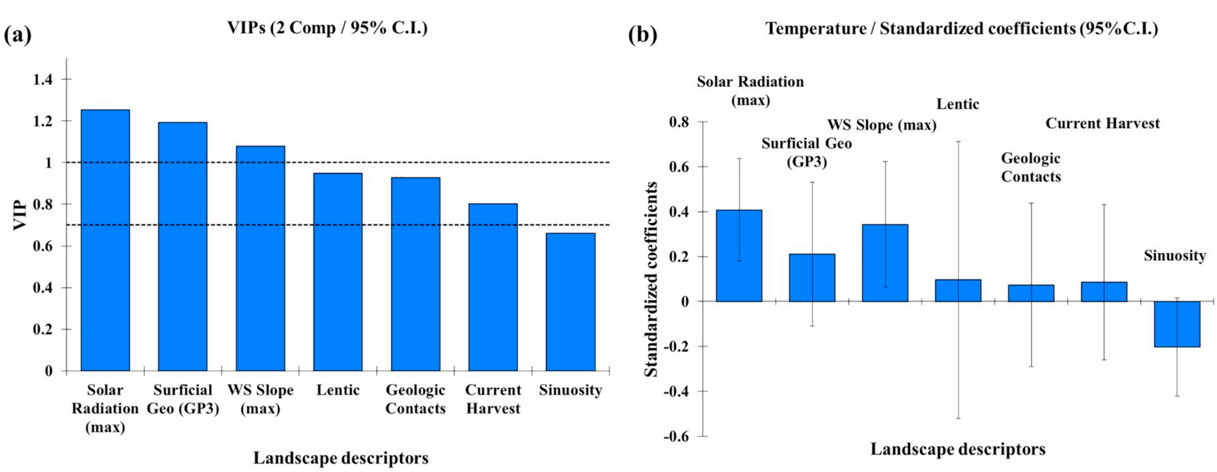
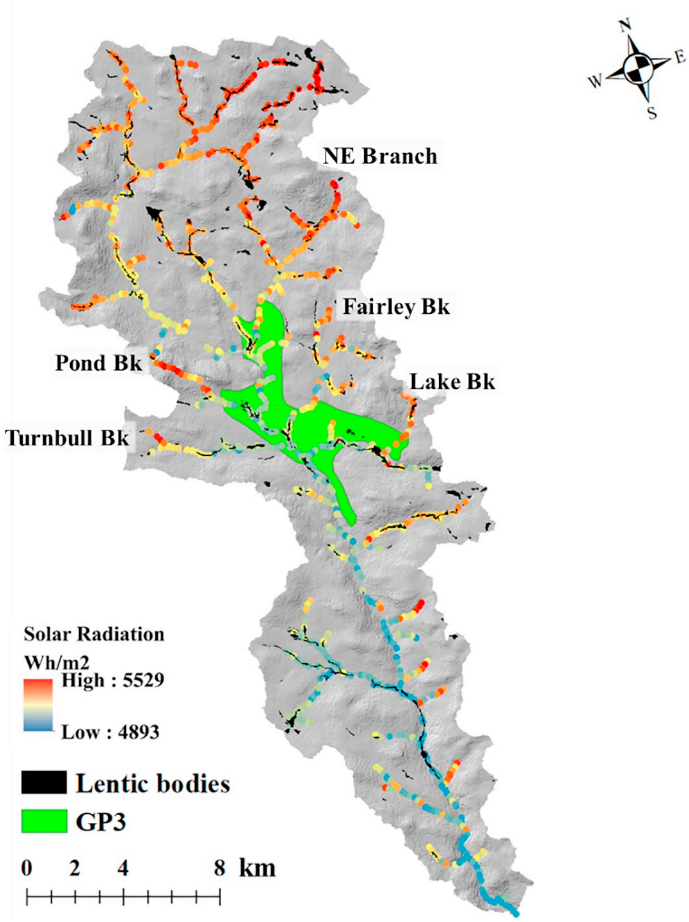


Fig. 5. (a) VIPs and (b) standardized coefficients (± 95% C.I.) for a PLS model with two latent vectors predicting the tributary watershed median surface water temperature within the Clearwater Brook watershed. Where 'Solar radiation (max)' is the maximum calculated solar radiation value (Wh/m^2) for each tributary; 'Surficial Geo (GP3)' is a glaciofluvial plain deposit composed of gravels, sands and silts, and generally > 1.5 m thick; 'WS slope (max)' is the maximum tributary watershed slope, 'Current harvest' is harvested area in the 7 years prior to TIR acquisition, and 'Sinuosity' is river sinuosity.

Coarse textured, glaciofluvial outwash material was also a positive, significant variable predicting temperature in the Clearwater Brook. These deposits are permeable which is usually associated with groundwater discharge or hyporheic processes in rivers (e.g., Wondzell and Gooseff, 2013; Wawrzyniak et al., 2016) that typically moderating temperature effects in flowing waters (e.g., Curry and Devito, 1996; Kurylyk et al., 2013). The deposit occurs in tributary watersheds that receive the highest levels of solar radiation exposure and inputs from



Tributary	*Solar Radiation (max) Wh/m²*	*GP3 (surficial deposit) km²*
Pond Bk	5577	1.8
NE Branch	5544	1.9
Turnbull Bk	5512	0.3
Lake Bk	5490	5.1
Fairley BK	5474	19
McCoy Bk	5463	0
Luke Bk	5452	0
Joe Bk	5450	0
Molasses Bk	5439	0
Moose Bk	5425	0
Otter Bk	5383	0
Redstone Bk	5362	0
Bear Bk	5360	0

Fig. 6. Spatial position of glaciofluvial plain (GP3) deposit, generally > 1.5 m and composed of gravel, sand, and minor silt, within the Clearwater Brook watershed, the accumulated solar radiation across the watershed, and the spatial position of lentic bodies (BK = brook).

upland lentic waterbodies within Clearwater Brook (Fig. 6). The permeability and valley position of these deposits also suggests an area of recharge concurrent with higher solar radiation and thus possible introduction of warmer water into shallow or local groundwater (Kurylyk et al., 2013) that appears to influence the river.

Lentic waterbodies (lakes, ponds, and beaver dams) were moderately significant and positively correlated with river temperatures in these highlands (1 < VIP > 0.7). The waterbodies are likely shallow as they sit in the low order portions of these watersheds, thus they absorb solar radiation and heat in summer and discharge warm water to the river (e.g., Collen and Gibson, 2000). However, beaver dams and ponds, can alter groundwater flow paths and stream hyporheic exchange creating complex effects in receiving rivers (e.g., Briggs et al., 2013; Weber et al., 2017). A better understanding of how landscape position of lentic body influences their role on river thermal regimes is required (Winter et al., 1998).

Interestingly, geological contact zones were projected as moderately significant and positively correlated with river temperature in both Highland region watersheds. The Miramichi Highlands are part of the Appalachian orogeny and its basement is heterogeneous with various discontinuities typical of mountainous regions (Caine and Tomusiak, 2003), comprising older and younger volcanic and sedimentary derived bedrock lithologies (Rampton et al., 1984). At contact zones contrasting bedrock types and permeability can influence groundwater transit time and flow path depth and modify groundwater and river base flow (Hale and McDonnell, 2016; Pfister et al., 2017). Older bedrock can be more fractured and more permeable than younger bedrock (Jefferson et al., 2010) and thus the contact zones in this study may alter gaining and losing characteristics for groundwater and thus affect the river's thermal regime (e.g., Winter et al., 1998; Saar, 2011). This process may explain the increase in river temperature noted along the main stem of Clearwater Brook. Here, the transition from a Middle Ordovician (≈465 million years ago (Mya)) granite deposit to a Middle Devonian (≈387.5 Mya) granite deposit underlies a 2.5 °C increase in river temperature along ≈5 km reach (Fig. 8).

Two characteristics of minor significance that influence river temperatures, and only in Clearwater Brook tributary watersheds, were percent coverage of recent harvesting and stream sinuosity. Harvesting may be significant in the Clearwater Brook, because this was the watershed with the most harvesting and potentially experienced reductions in interception and transpiration. Increased temperatures could be attributed to harvest activities in areas with shallow surface deposits that promote shallow water table depths and increases in temperatures of surface and subsurface water on route to the river (Alexander, 2006; Moore et al., 2005; Smerdon et al., 2009). Also noteworthy is the lack of influence of river sinuosity (meanders) in this study as moderation of river temperatures - decrease in summer and increase in winter- have been associated with the frequency of meanders that protrude into groundwater flow fields or promote hyporheic exchange flows (HEF) in other studies (Dugdale et al., 2015; Wondzell and Gooseff, 2013). Rivers in the two study physiographic units may vary little in sinuosity due partially to the depth and composition of both the bedrock and surficial geological materials that the river moves through (Langbein and Leopold, 1966). Further exploration of the extent and processes explaining the relationship of river temperature and these metrics is the topic of future research.

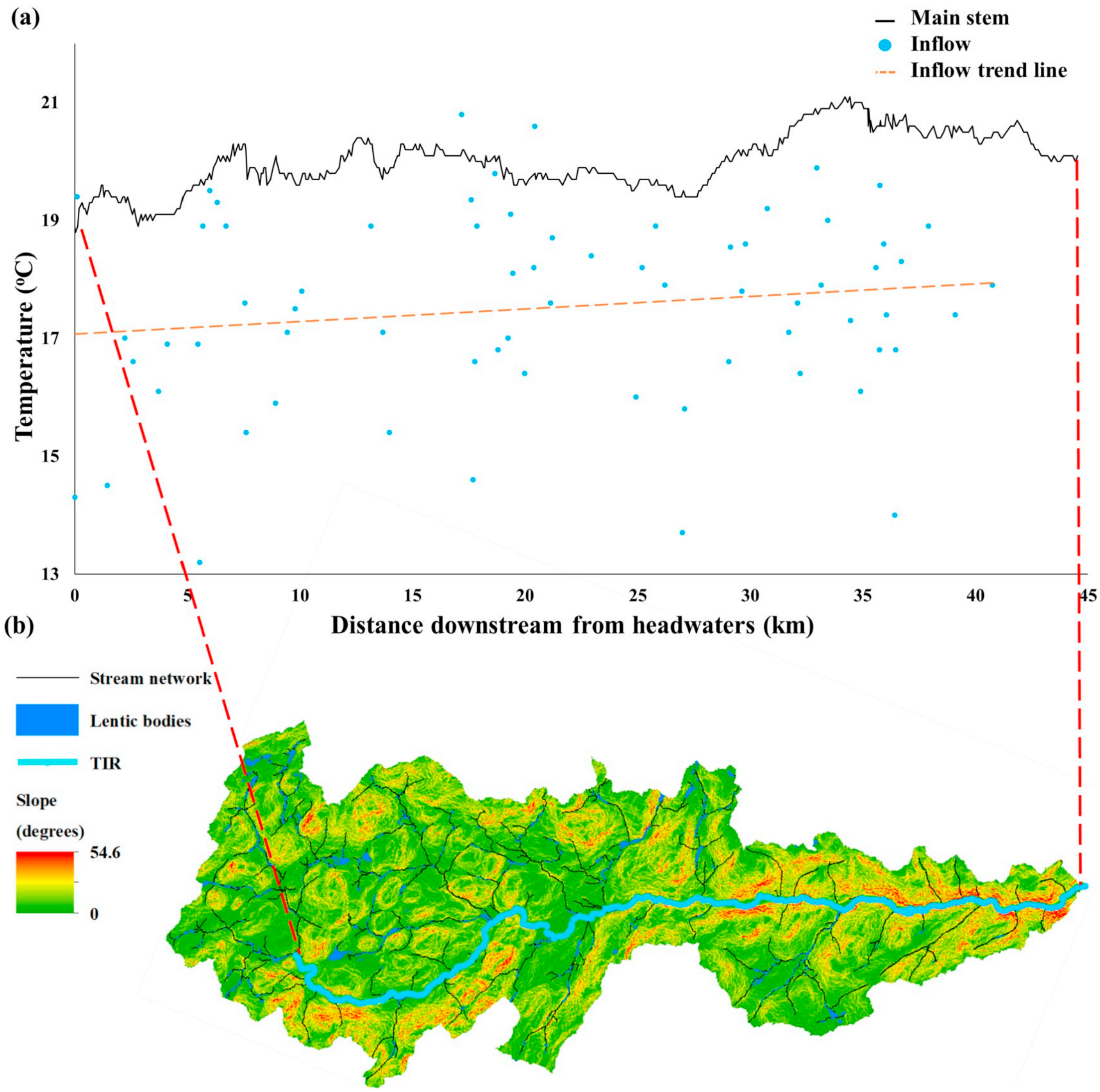


Fig. 7. (a) Clearwater Brook Longitudinal Temperature Profile (LTP) where km 0 identifies the base of the headwater basin. The black line denotes the main stem temperature profile, the blue dots indicates inflows, and the orange dashed line is the inflows trend line. (b) Lentic bodies – blue polygon, stream networks, and extent of TIR imposed on the slope within the Clearwater Brook's watershed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Maritime Lowland watersheds

In contrast to the Highlands watershed, for the physiographic setting of the Cains River maximum watershed elevation ('Maximum Elev'), percent of river moving through wetland ('% thru wetlands'), and total area of wetlands ('Wetlands') were significant, positive variables, whilst river slope ('Stream slope') in the watershed was a negative variable in projecting tributary river temperatures. The warmer tributary temperatures at the headwaters of the Cains watershed is likely related to the extensive wetlands and associated advective processes in this low relief upland region with shallow surficial deposits. Wetlands have high solar radiation exposure owing to the lack of solar interception, thus heat up in the summer – unless mitigated by groundwater (Winter et al., 1998). As these wetlands heat, they also increase the temperature of the receiving river. Additionally, this is a physiographic setting where groundwater development and flow are restricted, potentially resulting in upland and hillslope hydrological disconnection from rivers or wetlands source areas during the summer or drought periods (Devito and Hill, 1999), and thereby, leading to increases in the receiving rivers' temperature.

River slope was the only variable negatively correlated with river temperature. Typically, steep slopes are indicative of shallow surficial deposits, with shallow groundwater flow paths, and are more regulated by air temperatures, and climatic variation (Johnson et al., 2017; Briggs et al., 2017); however steep river slopes also typically experience low solar radiation exposure (Johnson, 2004). Nevertheless, the Cains Rivers' underlying geology is permeable, highly fractured sandstone and fluviatile conglomerates (Rampton et al., 1984). In this physiographic setting with permeable bedrock, we suggest that steep slopes in the main stem and its tributaries intersect slower and deeper groundwater with cooler temperature discharging from the under-lying lithology (e.g., Winter et al., 1998; Hale and M^cDonnell, 2016). In this setting, the potential for HEF also increases due to large hydraulic gradients and permeable substrate (Clark et al., 1999; Wondzell and Gooseff, 2013) and coupled with less solar radiation inputs cooler river temperatures occur in steeper reaches of the Cain's main stem and its tributaries (Fig. 10).

4.3. Interactions of physiography and catchment characteristics

Comparison of the Highlands and Lowland LTP illustrates how the difference in physiography, the depth, structure and configuration of

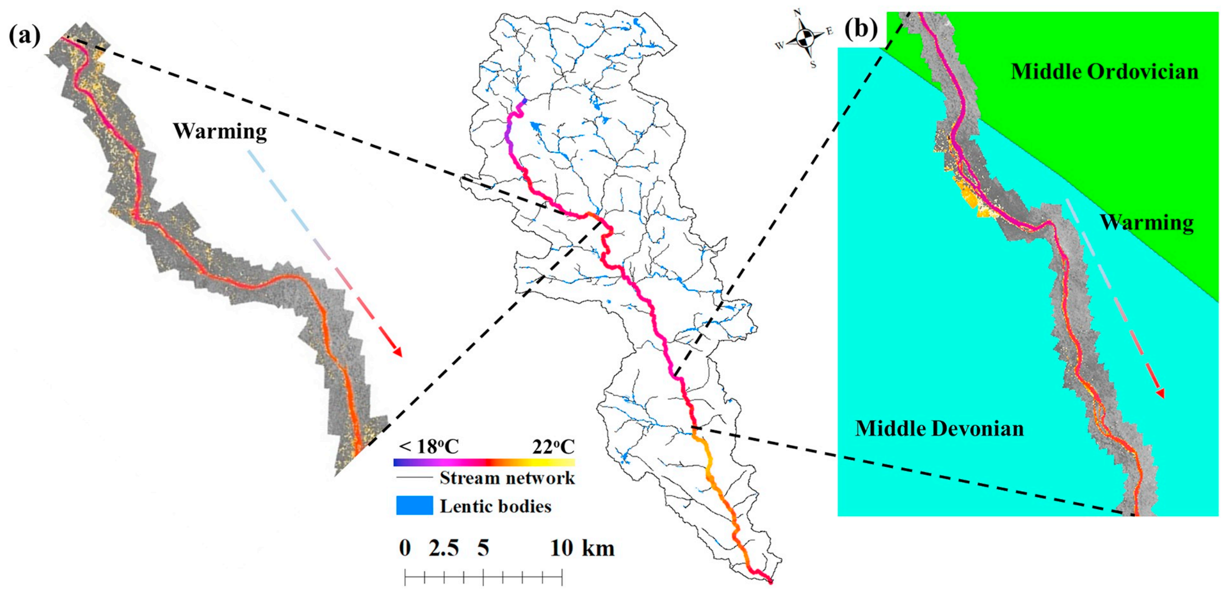


Fig. 8. Clearwater Brook main stem temperature gradient, where (a) is a reach with inputs from tributaries with high solar radiation exposures and lentic bodies warming in a downstream direction and, (b) is a warming reach where the river crosses a geological bedrock contact (Middle Ordovician upstream – Middle Devonian downstream).

geologic materials (i.e. HRA), influence how smaller scale variables (HU) function to influence river temperatures across different physiographic (i.e. management) units. For example, the substantial increase in temperature with migration through wetlands, and lentic water bodies was observed on all three rivers, but the magnitude of the influence differed with location along the river. In both Highland rivers, cool temperatures in the main stem and inflows were observed in the upstream semi-confined channel section, excluding wetland-derived inputs, and a warming trend was observed in the lower confined channel sections. The semi-confined channel sections on the headwaters are underlain by relatively deep coarse surficial deposits (Rampton et al., 1984) that promote groundwater flow and HEF which maintain cooler river temperatures. Inversely, steep slopes and the underlying geology on the river and adjacent hill sides result in channel confinement at the lower sections of the rivers. The confinement is associated with shallow surficial deposits and reduced groundwater storage, and HEF potential (Wondzell and Gooseff, 2013) and river temperatures are likely moderated by solar radiation and air temperature. In contrast, the Maritime Lowland has a physiographic setting with lower relief and is underlain by homogeneous fractured sandstone and fluviatile conglomerates, with deeper surficial deposition in the lower reaches. The decrease in main stem and inflow temperatures in a downstream direction of the Cains River may be explained by: 1) the absence of wetlands and advective warming in the lower reaches; 2) deep groundwater inputs from the fractured bedrock geology, 3) greater surficial deposit depths in the downstream reaches leading to cooler groundwater inflow streams and seeps, and 4) river gradients increase in the lower sections leading to an increase in potential HEF processes (Wondzell and Gooseff, 2013).

The temperature of the small inflows and seeps along the LTP follow a similar trend to the main stem in both physiographic settings. The ephemeral nature of inflows and seeps of the Highland rivers is

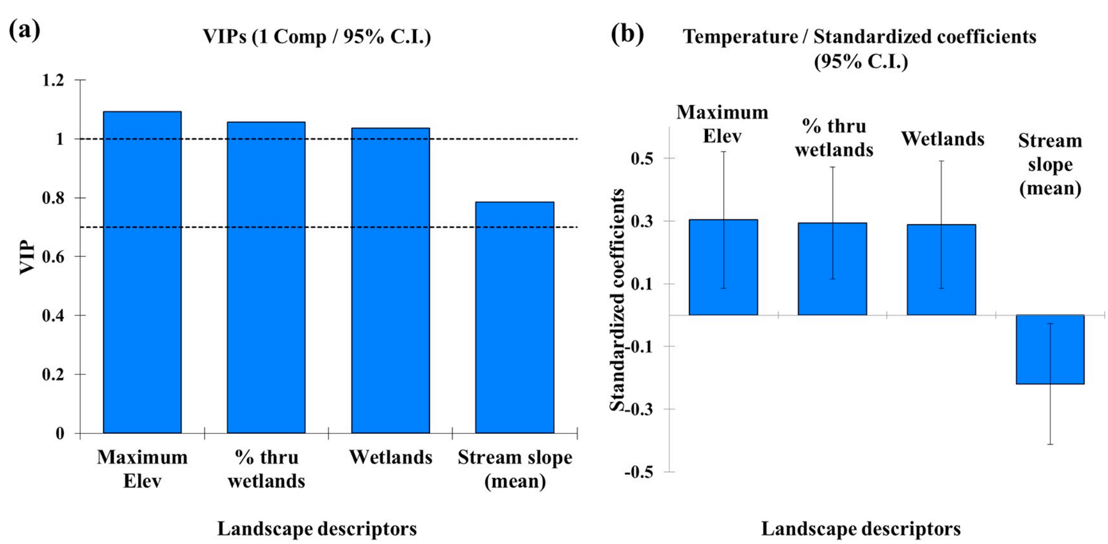


Fig. 9. (a) VIPs; and (b) standardized coefficients (± 95% C.I.) for a PLS model with 1 latent vector predicting the tributary median surface water temperature within the Cains River watershed. Where 'WS Elev (max)' is the maximum watershed elevation in the sampled tributary; 'Wetlands' are area of wetlands upstream of the observed temperature point; '% thru WL' is the length of river running through a wetland complex; and 'Stream Slope (mean)' is the mean river slope in the sampled tributary.

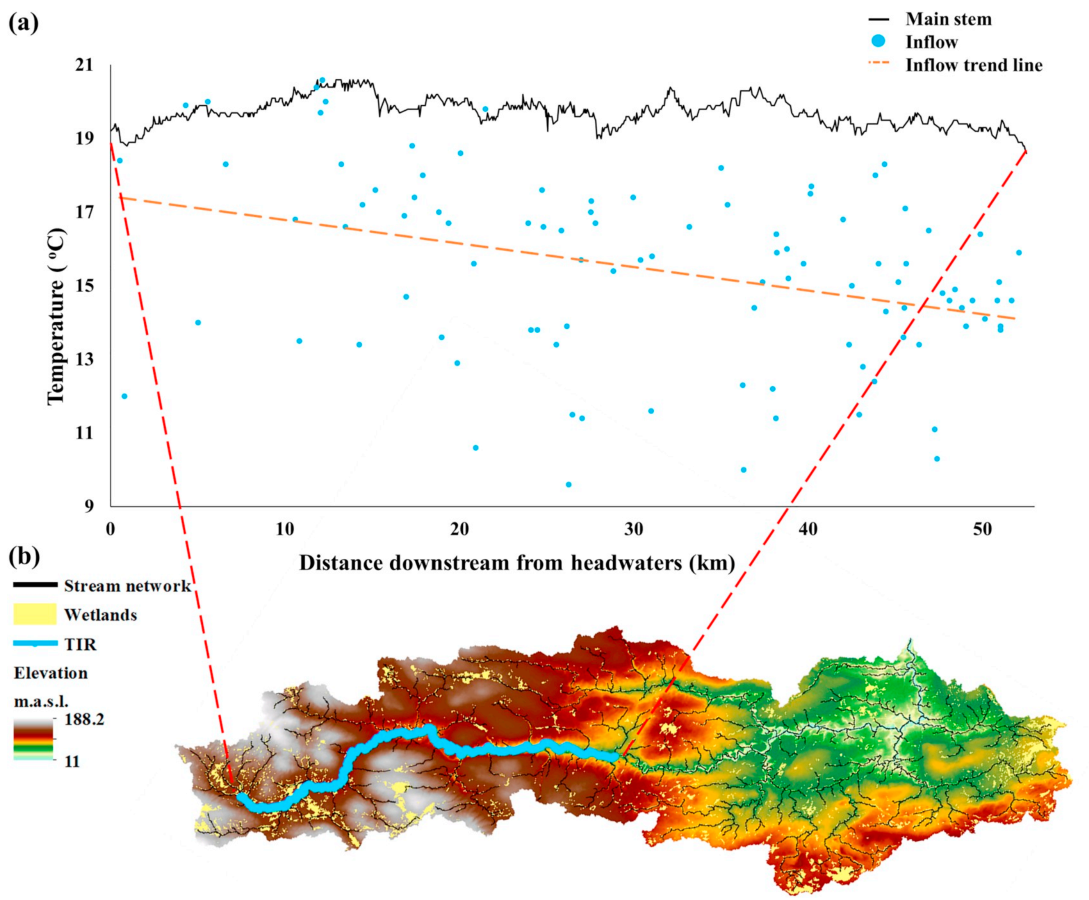


Fig. 10. (a) Cains River LTP where km 0 identifies the headwater reaches, and moving downstream. The black line denotes the main stem temperature profile, the blue dots indicates inflows, and the orange trend line is the linear regression (LR) for inflows. (b) displays TIR extent and wetland distribution imposed on the Cains River watershed's elevation profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

apparent by the variability in number and spatial distribution in Burnthill Brook (Fig. 4) and Clearwater Brook (Fig. 7). The greater number of inflows observed in the Clearwater may be a function of inter-annual variability in precipitation, as the Clearwater was sampled during a wetter year (see Table 2). The large number of small inflows and seeps on the Cains reflects deeper surficial deposits and permeable bedrock, and thus the temperatures are also more temporally stable than in the Highland watersheds. The ephemeral character of small inflows and seeps in steep, confined river valley sections, their role in mitigating increases in river temperature and persistence with climate change requires further research.

5. Conclusion

Our results highlight the concept that a river is connected to its valley (Hynes, 1975) and thus understanding the spatial variability in river thermal regimes requires knowledge of the underlying physiography and geomorphology of the landscape. Further, our results establish the need to begin thinking about past geological and climatic processes. We observed that surface water temperatures in highland orogenous regions were best predicted by solar radiation, watershed slope, and geologic contact zones, and in lowland low relief watersheds with homogenous sedimentary bedrock, by the prevalence of wetlands and river slope. The detailed processes controlling river temperature requires further study, however, this research exemplifies that the river valley landscape, and adjacent hillslopes and uplands, influences surface and groundwater interactions across broad and localized scales.

This research gives additional credence to the fact surface and groundwater interactions are key factors regulating thermal processes in flowing waters, thermal refugia, and ecohydrologic processes, for river ecosystems (e.g., Briggs and Hare, 2018). Subsurface processes are often overlooked in river temperature modelling (Caissie et al., 2007) due to inherent heterogeneities and complexities associated with data acquisition as measurement scale increases. However, the riverscape is best viewed as a confluence of surface water and groundwater (Winter et al., 1998; Hynes, 1975), and therefore bedrock and surficial geology influence on subsurface processes will need increasing consideration for river temperature modelling (e.g., Constantz, 1998; Tague and Grant, 2004; Tague et al., 2008; Larocque et al., 2010; Johnson et al., 2017). Additionally, these findings indicate that surficial features alone are insufficient to predict the complex hydrology of the vadose and phreatic zones (e.g., Devito et al., 1996; Tague et al., 2008), and further highlights the limitations associated with watershed delineation based entirely on topography (Tóth, 1962; Winter et al., 2003).

The statistical models presented here are used largely as a tool to test and falsify conceptual models, to help tease-out the possible processes involved in regulating the thermal regimes of rivers. We continue to refine our models by including spatial field data, such as river stage (Hester et al., 2013), and geologic structure (Tóth, 1963; Tague et al., 2007), and remotely sensed data, such as high resolution LiDAR (Wawrzyniak et al., 2017), and bathymetry (Legleiter et al., 2009). The primary function of such models is to strengthen our predictions about river temperatures across changing landscapes, e.g., under forest harvest, mineral resource extraction, urban development, and in a warming climate. This is especially important for Atlantic Salmon (*Salmo salar*) and Brook Charr (*Salvelinus fontinalis*) populations in the southern extent of eastern Canada, where forestry and mineral resource extraction are omnipresent.

Acknowledgements

First, we would like to thank our lord Pisces. The authors wish to thank NSERC (184846-2011-RGPIN), New Brunswick's Environmental Trust Fund and Wildlife Trust Fund, the Miramichi Salmon Association, and J.D. Irving, Limited for funding support. M. Gautreau, B. Wallace (CRI/UNB), and staff of J.D. Irving, Limited and Quantum Spatial provided logistic support. The authors also thank two anonymous reviewers for their insightful and constructive comments, which have strengthened this manuscript. T. Dilts provided access to the Stream Sinuosity and Gradient toolbox. Geospatial information was provided through GeoNB, New Brunswick Department of Natural Resources Forest Management Branch, Environment Canada, and NASA. Additionally, the first author would like to thank the Miramichi Salmon Association (MSA), Jack T.H. Fenety, Bud and Peggy Bird, Mr. and Mrs. Art Van Slyke, and the Canadian Rivers Institute for generous scholarships.

References

Abdi, H., 2010. Partial least squares regression and projection on latent structure regression (PLS Regression). Wiley Interdiscip. Rev. Comput. Stat. 2 (1), 97–106. John Wiley & Sons, Inc.. https://doi.org/10.1002/wics.51.

Alexander, M.D., 2006. The Thermal Regime of Shallow Groundwater in a Clearcut and a Forested Streamside Buffer. University of New Brunswick.

Breau, C., Cunjak, R.A., Peake, S.J., 2011. Behaviour during elevated water temperatures: can physiology explain movement of juvenile Atlantic salmon to cool water? J. Anim. Ecol. 80 (4), 844–853. Blackwell Publishing Ltd.. https://doi.org/10.1111/j.1365-2656.2011.01828.x.

Briggs, M.A., Hare, D.K., 2018. Explicit consideration of preferential groundwater discharges as surface water ecosystem control points. Hydrol. Process. 32 (15), 2435–2440. Wiley-Blackwell. https://doi.org/10.1002/hyp.13178.

Briggs, M.A., Lautz, L.K., Hare, D.K., González-Pinzón, R., 2013. Relating hyporheic fluxes, residence times, and redox-sensitive biogeochemical processes upstream of beaver dams. Freshw. Sci. 32 (2), 622–641. The University of Chicago Press. https://doi.org/10.1899/12-110.1.

Briggs, M.A., Lane, J.W., Snyder, C.D., White, E.A., Johnson, Z.C., Nelms, D.L., Hitt, N.P., 2017. Shallow bedrock limits groundwater seepage-based headwater climate refugia. Limnol. - Ecol. Manag. Inl. Waters. Urban Fischer. https://doi.org/10.1016/J.LIMNO.2017.02.005.

Briggs, M.A., Johnson, Z.C., Snyder, C.D., Hitt, N.P., Kurylyk, B.L., Lautz, L., Irvine, D.J., Hurley, S.T., Lane, J.W., 2018. Inferring watershed hydraulics and cold-water habitat persistence using multi-year air and stream temperature signals. Sci. Total Environ. 636, 1117–1127. Elsevier. https://doi.org/10.1016/J.SCITOTENV.2018.04.344.

Caine, J.S., Tomusiak, S.R.A., 2003. Brittle structures and their role in controlling porosity and permeability in a complex Precambrian crystalline-rock aquifer system in the Colorado Rocky Mountain Front Range. Geol. Soc. Am. Bull. 115 (11), 1410. GeoScienceWorld. https://doi.org/10.1130/B25088.1.

Caissie, D., 2006. The thermal regime of rivers: a review. Freshw. Biol. 51 (8), 1389–1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x.

Caissie, D., Satish, M.G., El-Jabi, N., 2007. Predicting water temperatures using a deterministic model: application on Miramichi River catchments (New Brunswick, Canada). J. Hydrol. 336 (3–4), 303–315. https://doi.org/10.1016/j.jhydrol.2007.01.008.

Carrascal, L.M., Galván, I., Gordo, O., 2009. Partial Least Squares Regression as an Alternative to Current Regression Methods Used in Ecology. Wiley Nordic Society Oikoshttps://doi.org/10.2307/40235374.

Chadwick, J.G., Nislow, K.H., McCormick, S.D., McCormick, S.D., 2015. Thermal onset of cellular and endocrine stress responses correspond to ecological limits in brook trout, an iconic cold-water fish. Conserv. Physiol. 3 (1), cov017. Oxford University Press. https://doi.org/10.1093/conphys/cov017.

Chin, W.W., 1998. The partial least squares approach to structural equation modeling. In: Marcoulides, G.A. (Ed.), Modern Methods for Business Research. Lawrence Erlbaum Associates Available from. https://books.google.com/books?hl=en&lr=&id=EDZ5AgAAQBAJ&oi=fnd&pg=PA295&dq=Chin+1998+PLS&ots=48sJ6up5fp&sig=g2Hie3Yy1qK1G8VnO8OVS5kR5TE, Accessed date: 17 October 2018.

Clark, E., Webb, B.W., Ladle, M., 1999. Microthermal gradients and ecological implications in Dorset rivers. Hydrol. Process. 13 (3), 423–438.

Collen, P., Gibson, R.J., 2000. The general ecology of beavers (Castor spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. Rev. Fish Biol. Fish. 10 (4), 439–461. Kluwer Academic Publishers. https://doi.org/10.1023/A:1012262217012.

Constantz, J., 1998. Interaction between stream temperature, streamflow, and groundwater exchanges in alpine streams. Water Resour. Res. 34 (7), 1609–1615. https://doi.org/10.1029/98WR00998.

Cowood, A.L., Moore, C.L., Cracknell, M.J., Young, J., Muller, R., Nicholson, A.T., Wooldridge, A.C., Jenkins, B.R., Cook, W., 2017. Expansion of landscape characterisation methods within the Hydrogeological Landscape Framework: application in the Australian Capital Territory. Aust. J. Earth Sci. 64 (8), 1073–1084. Taylor & Francis. https://doi.org/10.1080/08120099.2017.1255656.

Cunjak, R.A., 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Can. J. Fish. Aquat. Sci. 53 (S1), 267–282. NRC Research Press Ottawa, Canada. https://doi.org/10.1139/f95-275.

Cunjak, R.A., Newbury, R.W., 2005. Atlantic coast rivers of Canada. In: Rivers of North America. Elsevier, pp. 938–980. https://doi.org/10.1016/B978-012088253-3/50024-9.

Curry, R.A., 2007. Late glacial impacts on dispersal and colonization of Atlantic Canada and Maine by freshwater fishes. Quat. Res. 67 (2), 225–233. No longer published by Elsevier. https://doi.org/10.1016/J.YQRES.2006.11.002.

Curry, R.A., Devito, K.J., 1996. Hydrogeology of brook trout (*Salvelinus fontinalis*) spawning and incubation habitats: implications for forestry and land use development. Can. J. For. Res. 26 (5), 767–772. NRC Research Press Ottawa, Canada. https://doi.org/10.1139/x26-086.

Curry, R.A., Noakes, D.L.G., 1995. Groundwater and the selection of spawning sites by brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 52 (8), 1733–1740. NRC Research Press Ottawa, Canada. https://doi.org/10.1139/f95-765.

Curry, R.A., Scruton, D.A., Clarke, K.D., 2002. The thermal regimes of brook trout incubation habitats and evidence of changes during forestry operations. Can. J. For. Res. 32 (7), 1200–1207. https://doi.org/10.1139/x02-046.

Detty, J.M., McGuire, K.J., 2010. Threshold changes in storm runoff generation at a till-mantled headwater catchment. Water Resour. Res. 46 (7). https://doi.org/10.1029/2009WR008102. n/a-n/a.

Devito, K.J., Hill, A.R., 1999. Sulphate mobilization and pore water chemistry in relation to groundwater hydrology and summer drought in two conifer swamps on the Canadian Shield. Water Air Soil Pollut. 113 (1/4), 97–114. Kluwer Academic Publishers. https://doi.org/10.1023/A:1005081505086.

Devito, K.J., Hill, A.R., Roulet, N., 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. J. Hydrol. 181 (1–4), 127–147. Elsevier. https://doi.org/10.1016/0022-1694(95)02912-5.

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., Smerdon, B., 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? Hydrol. Process. 19 (8), 1705–1714. John Wiley & Sons, Ltd.. https://doi.org/10.1002/hyp.5881.

Devito, K.J., Hokanson, K.J., Moore, P.A., Kettridge, N., Anderson, A.E., Chasmer, L., Hopkinson, C., Lukenbach, M.C., Mendoza, C.A., Morissette, J., Peters, D.L., Petrone, R.M., Silins, U., Smerdon, B., Waddington, J.M., 2017. Landscape controls on long-term runoff in subhumid heterogeneous Boreal Plains catchments. Hydrol. Process. 31 (15), 2737–2751. https://doi.org/10.1002/hyp.11213.

Dilts, T., 2015. Stream Gradient & Sinuosity Toolbox for ArcGISv10. Available from. https://www.arcgis.com/home/item.html?id=c8eb4ce1384e45258ccba1b33cd4e3cb, Accessed date: 29 January 2018.

Dugdale, S.J., Bergeron, N.E., St-Hilaire, A., 2015. Spatial distribution of thermal refuges analysed in relation to riverscape hydromorphology using airborne thermal infrared imagery. Remote Sens. Environ. 160, 43–55. Elsevier. https://doi.org/10.1016/J.RSE.2014.12.021.

Dugdale, S.J., Franssen, J., Corey, E., Bergeron, N.E., Lapointe, M., Cunjak, R.A., 2016. Main stem movement of Atlantic salmon parr in response to high river temperature. Ecol. Freshw. Fish 25 (3), 429–445. https://doi.org/10.1111/eff.12224.

Dunne, T., Leopold, L.B., 1978. Water in environmental planning. Macmillan.

Ebersole, J.L., Liss, W.J., Frissell, C.A., 2003. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Can. J. Fish. Aquat. Sci. 60 (10), 1266–1280. NRC Research Press Ottawa, Canada. https://doi.org/10.1139/f03-107.

Eriksson, L., Hermens, J.L.M., Johansson, E., Verhaar, H.J.M., Wold, S., 1995. Multivariate analysis of aquatic toxicity data with PLS. Aquat. Sci. 57 (3), 217–241. Birkhäuser-Verlag. https://doi.org/10.1007/BF00877428.

Esri, 2018. GIS Mapping Software, Spatial Data Analytics & Location Platform. Available from. https://www.esri.com/en-us/home, Accessed date: 29 May 2018.

French, W., 2014. Protected from the Elements: Winter Ecology of Brown Trout in Groundwater Buffered Streams. Available from. https://conservancy.umn.edu/handle/11299/174220, Accessed date: 29 January 2018.

Fu, P., Rich, P.M., 2002. A geometric solar radiation model with applications in agriculture and forestry. Comput. Electron. Agric. 37 (1–3), 25–35.

Fuhrman, A.E., Larsen, D.A., Steel, E.A., Young, G., Beckman, B.R., 2018. Chinook salmon emergence phenotypes: describing the relationships between temperature, emergence timing and condition factor in a reaction norm framework. Ecol. Freshw. Fish 27 (1), 350–362. https://doi.org/10.1111/eff.12351.

Fullerton, A.H., Torgersen, C.E., Lawler, J.J., Steel, E.A., Ebersole, J.L., Lee, S.Y., 2018. Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. Aquat. Sci. 80 (1), 3. Springer International Publishing. https://doi.org/10.1007/s00027-017-0557-9.

Garner, G., Malcolm, I.A., Sadler, J.P., Hannah, D.M., 2017. The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics. J. Hydrol. 553, 471–485. Elsevier. https://doi.org/10.1016/J.JHYDROL.2017.03.024.

Goniea, T.M., Keefer, M.L., Bjornn, T.C., Peery, C.A., Bennett, D.H., Stuehrenberg, L.C., 2006. Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. Trans. Am. Fish. Soc. 135 (2), 408–419.

Hale, V.C., McDonnell, J.J., 2016. Effect of bedrock permeability on stream base flow mean transit time scaling relations: 1. A multiscale catchment intercomparison. Water Resour. Res. 52 (2), 1358–1374. Wiley-Blackwell. https://doi.org/10.1002/2014WR016124.

Hatch, C.E., Fisher, A.T., Revenaugh, J.S., Constantz, J., Ruehl, C., 2006. Quantifying surface water-groundwater interactions using time series analysis of streambed thermal records: method development. Water Resour. Res. 42 (10). https://doi.org/10.1029/2005WR004787.

Hester, E.T., Young, K.I., Widdowson, M.A., 2013. Mixing of surface and groundwater induced by riverbed dunes: implications for hyporheic zone definitions and pollutant reactions. Water Resour. Res. 49 (9), 5221–5237. https://doi.org/10.1002/wrcr.20399.

Hrachowitz, M., Soulsby, C., Imholt, C., Malcolm, I.a., Tetzlaff, D., 2010. Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape

controls and climate change on maximum temperatures. Hydrol. Process. 24 (July), 3374–3391. https://doi.org/10.1002/hyp.7756.
Hynes, H.B.N., 1975. The stream and its valley. SIL Proceedings, 1922–2010 19 (1), 1. 15. Taylor & Francis. https://doi.org/10.1080/03680770.1974.11896033.
Isaak, D., Luce, C., Rieman, B., Nagel, D., Peterson, E., Horan, D., Parkes, S., Chandler, G., 2009. Effects of climate change and recent wildfires on stream temperature and thermal habitat for two salmonids in a mountain river network. Ecol. Appl. 20 (5), 100319061507001. https://doi.org/10.1890/09-0822.
Isaak, D.J., Young, M.K., Nagel, D.E., Horan, D.L., Groce, M.C., 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. Glob. Chang. Biol. 21 (7), 2540–2553. https://doi.org/10.1111/gcb.12879.
Isaak, D.J., Wenger, S.J., Young, M.K., 2017. Big biology meets microclimatology: defining thermal niches of ectotherms at landscape scales for conservation planning. Ecol. Appl. 27 (3), 977–990. https://doi.org/10.1002/eap.1501.
James, E.R., Manga, M., Rose, T.P., Hudson, G.B., 2000. The use of temperature and the isotopes of O, H, C, and noble gases to determine the pattern and spatial extent of groundwater flow. J. Hydrol. 237 (1–2), 100–112.
Jefferson, A., Grant, G.E., Lewis, S.L., Lancaster, S.T., 2010. Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA. Earth Surf. Process. Landf. https://doi.org/10.1002/esp.1976. n/a-n/a.
Johnson, S.L., 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Can. J. Fish. Aquat. Sci. 61 (6), 913–923. https://doi.org/10.1139/F04-040.
Johnson, Z.C., Snyder, C.D., Hitt, N.P., 2017. Landform features and seasonal precipitation predict shallow groundwater influence on temperature in headwater streams. Water Resour. Res. 53 (7), 5788–5812.
Koirala, S., Hirabayashi, Y., Mahendran, R., Kanae, S., 2014. Global assessment of agreement among streamflow projections using CMIP5 model outputs. Environ. Res. Lett. 9 (6), 64017. IOP Publishing. https://doi.org/10.1088/1748-9326/9/6/064017.
Kurylyk, B.L., Bourque, C.P.-A., MacQuarrie, K.T.B., 2013. Potential surface temperature and shallow groundwater temperature response to climate change: an example from a small forested catchment in east-central New Brunswick (Canada). Hydrol. Earth Syst. Sci. 17 (7), 2701–2716. https://doi.org/10.5194/hess-17-2701-2013.
Kurylyk, B.L., MacQuarrie, K.T.B., Caissie, D., McKenzie, J.M., 2014. Shallow groundwater thermal sensitivity to climate change and land cover disturbances: derivation of analytical expressions and implications for stream temperature projections. Hydrol. Earth Syst. Sci. Discuss. 11, 12573–12626. https://doi.org/10.5194/hessd-11-12573-2014.
Langbein, W.B., Leopold, L.B., 1966. River meanders - theory of minimum variance. In: Professional Paper, https://doi.org/10.3133/PP422H.
Larocque, M., Fortin, V., Pharand, M.C., Rivard, C., 2010. Groundwater contribution to river flows – using hydrograph separation, hydrological and hydrogeological models in a southern Quebec aquifer. Hydrol. Earth Syst. Sci. Discuss. 7 (5), 7809–7838. https://doi.org/10.5194/hessd-7-7809-2010.
Legleiter, C.J., Roberts, D.A., Lawrence, R.L., 2009. Spectrally based remote sensing of river bathymetry. Earth Surf. Process. Landf. 34 (8), 1039–1059. John Wiley & Sons, Ltd.. https://doi.org/10.1002/esp.1787.
Li, Z., 2014. Watershed modeling using arc hydro based on DEMs: a case study in Jackpine watershed. Environ. Syst. Res. 3 (1), 11.
Linnansaari, T., Cunjak, R.A., 2010. Patterns in apparent survival of Atlantic salmon (*Salmo salar*) parr in relation to variable ice conditions throughout winter. Can. J. Fish. Aquat. Sci. 67 (11), 1744–1754. https://doi.org/10.1139/F10-093.
Majerova, M., Neilson, B.T., Schmadel, N.M., Wheaton, J.M., Snow, C.J., 2015. Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream. Hydrol. Earth Syst. Sci. 19 (8), 3541–3556. https://doi.org/10.5194/hess-19-3541-2015.
Malcolm, I.A., Soulsby, C., Youngson, A.F., Hannah, D.M., McLaren, I.S., Thorne, A., 2004. Hydrological influences on hyporheic water quality: implications for salmon egg survival. Hydrol. Process. 18 (9), 1543–1560. John Wiley & Sons, Ltd.. https://doi.org/10.1002/hyp.1405.
McCullough, D.A., Bartholow, J.M., Jager, H.I., Beschta, R.L., Cheslak, E.F., Deas, M.L., Ebersole, J.L., Foott, J.S., Johnson, S.L., Marine, K.R., Mesa, M.G., Petersen, J.H., Souchon, Y., Tiffan, K.F., Wurtsbaugh, W.A., 2009. Research in thermal biology: burning questions for coldwater stream fishes. Rev. Fish. Sci. 17 (1), 90–115. https://doi.org/10.1080/10641260802590152.
Monk, W.A., Wilbur, N.M., Allen Curry, R., Gagnon, R., Faux, R.N., 2013. Linking landscape variables to cold water refugia in rivers. J. Environ. Manag. 118, 170–176. Elsevier Ltd.. https://doi.org/10.1016/j.jenvman.2012.12.024.
Moore, R.D., Spittlehouse, D.L., Story, A., 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. J. Am. Water Resour. Assoc. 41 (4), 813–834. https://doi.org/10.1111/j.1752-1688.2005.tb03772.x.
Petty, J.T., Thorne, D., Huntsman, B.M., Mazik, P.M., 2014. The temperature–-productivity squeeze: constraints on brook trout growth along an Appalachian river continuum. Hydrobiologia 727 (1), 151–166. Springer International Publishing. https://doi.org/10.1007/s10750-013-1794-0.
Pfister, L., Martínez-Carreras, N., Hissler, C., Klaus, J., Carrer, G.E., Stewart, M.K., McDonnell, J.J., 2017. Bedrock geology controls on catchment storage, mixing, and release: a comparative analysis of 16 nested catchments. Hydrol. Process. 31 (10), 1828–1845. https://doi.org/10.1002/hyp.11134.
Rampton, V.N., Gauthier, R.C., Thibault, J., Seaman, A.A., 1984. Quaternary geology of New Brunswick. In: Memoir 416.
Saar, M.O., 2011. Review: geothermal heat as a tracer of large-scale groundwater flow and as a means to determine permeability fields. Hydrogeol. J. 19 (1), 31–52. Springer-Verlag. https://doi.org/10.1007/s10040-010-0657-2.
Sharma, P., Kim, K., 2012. Model selection in information systems research using partial least squares based structural equation modeling. In: ICIS 2012 Proc. Available from. https://aisel.aisnet.org/icis2012/proceedings/ResearchMethods/6, Accessed date: 29 January 2018.
Smerdon, B.D., Redding, T.E., Beckers, J., 2009. An overview of the effects of forest management on groundwater hydrology. BC J. Ecosyst. Manag. 10 (1), 22–44. Available from. http://jem-online.org/index.php/jem/article/view/409.
Soulsby, C., Tetzlaff, D., Dunn, S.M., Waldron, S., 2006. Scaling up and out in runoff process understanding: insights from nested experimental catchment studies. Hydrol. Process. 20 (11), 2461–2465. John Wiley & Sons, Ltd.. https://doi.org/10.1002/hyp.6338.
Steel, E.A., Beechie, T.J., Torgersen, C.E., Fullerton, A.H., 2017. Envisioning, quantifying, and managing thermal regimes on river networks. Bioscience 67 (6), 506–522. Oxford University Press. https://doi.org/10.1093/biosci/bix047.
Tague, C., Grant, G.E., 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. Water Resour. Res. 40 (4). https://doi.org/10.1029/2003WR002629.
Tague, C., Farrell, M., Grant, G., Lewis, S., Rey, S., 2007. Hydrogeologic controls on summer stream temperatures in the McKenzie River basin, Oregon. Hydrol. Process. 21 (24), 3288–3300. John Wiley & Sons, Ltd.. https://doi.org/10.1002/hyp.6538.
Tague, C., Grant, G., Farrell, M., Choate, J., Jefferson, A., 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. Clim. Chang. 86 (1–2), 189–210. https://doi.org/10.1007/s10584-007-9294-8.
Torgersen, C.E., Price, D.M., Li, H.W., McIntosh, B.A., 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecol. Appl. 9 (1), 301–319. Wiley-Blackwell. https://doi.org/10.1890/1051-0761(1999)009[0301:MTRASH]2.0.CO;2.
Tóth, J., 1962. A theory of groundwater motion in small drainage basins in central Alberta, Canada. J. Geophys. Res. 67 (11), 4375–4388. https://doi.org/10.1029/JZ067i011p04375.
Tóth, J., 1963. A theoretical analysis of groundwater flow in small drainage basins. J. Geophys. Res. 68 (16), 4795–4812. https://doi.org/10.1029/JZ068i016p04795.
Ver Hoef, J.M., Peterson, E.E., 2010. A moving average approach for spatial statistical models of stream networks. J. Am. Stat. Assoc. 105 (489), 6–18. https://doi.org/10.1198/jasa.2009.ap08248.
Vidon, P., Smith, A.P., 2007. Upland controls on the hydrological functioning of riparian zones in glacial till valleys of the Midwest1. JAWRA J. Am. Water Resour. Assoc. 43 (6), 1524–1539. Blackwell Publishing Ltd.. https://doi.org/10.1111/j.1752-1688.2007.00125.x.
van Vliet, M.T.H., Franssen, W.H.P., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., Kabat, P., 2013. Global river discharge and water temperature under climate change. Glob. Environ. Chang. 23 (2), 450–464. Pergamon. https://doi.org/10.1016/J.GLOENVCHA.2012.11.002.
Warren, R., Price, J., Fischlin, A., de la Nava Santos, S., Midgley, G., 2011. Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. Clim. Chang. 106 (2), 141–177. Springer Netherlands. https://doi.org/10.1007/s10584-010-9923-5.
Wawrzyniak, V., Piégay, H., Allemand, P., Vaudor, L., Goma, R., Grandjean, P., 2016. Effects of geomorphology and groundwater level on the spatio-temporal variability of riverine cold water patches assessed using thermal infrared (TIR) remote sensing. Remote Sens. Environ. 175, 337–348. Elsevier. https://doi.org/10.1016/J.RSE.2015.12.050.
Wawrzyniak, V., Allemand, P., Bailly, S., Lejot, J., Piégay, H., 2017. Coupling LiDAR and thermal imagery to model the effects of riparian vegetation shade and groundwater inputs on summer river temperature. Sci. Total Environ. 592, 616–626. https://doi.org/10.1016/j.scitotenv.2017.03.019.
Weber, N., Bouwes, N., Pollock, M.M., Volk, C., Wheaton, J.M., Wathen, G., Wirtz, J., Jordan, C.E., 2017. Alteration of stream temperature by natural and artificial beaver dams. PLoS One 12 (5), e0176313. Public Library of Science. https://doi.org/10.1371/journal.pone.0176313.
Westhoff, M.C., Gooseff, M.N., Bogaard, T.A., Savenije, H.H.G., 2011. Quantifying hyporheic exchange at high spatial resolution using natural temperature variations along a first-order stream. Water Resour. Res. 47 (10). https://doi.org/10.1029/2010WR009767.
Wilbur, N., 2012. Characterizing Thermal Refugia for Brook Trout (*Salvelinus fontinalis*) and Atlantic Salmon (*Salmo salar*) in the Cains River, New Brunswick. University of New Brunwick, Canada.
Williams, H., 1979. Appalachian Orogen in Canada. Can. J. Earth Sci. 16 (3), 792–807. NRC Research Press Ottawa, Canada. https://doi.org/10.1139/e79-070.
Winter, T.C., 2001. The concept of hydrologic landscapes. J. Am. Water Resour. Assoc. 37 (2), 335–349. Wiley/Blackwell (10.1111). https://doi.org/10.1111/j.1752-1688.2001.tb00973.x.
Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M., 1998. Ground Water and Surface Water: A Single Resource. 79 USGS Publ.https://doi.org/10.3389/fpsyg.2012.00044.
Winter, T.C., Rosenberry, D.O., LaBaugh, J.W., 2003. Where does the ground water in small watersheds come from? Ground Water 41 (7), 989–1000. Blackwell Publishing Ltd.. https://doi.org/10.1111/j.1745-6584.2003.tb02440.x.
Wold, S., Ruhe, A., Wold, H., Dunn III, W.J., 1984. The collinearity problem in linear regression. The partial least squares (PLS) approach to generalized inverses. SIAM J. Sci. Stat. Comput. 5 (3), 735–743. Society for Industrial and Applied Mathematics. https://doi.org/10.1137/0905052.
Wold, S., Sjöström, M., Eriksson, L., 2001. PLS-regression: a basic tool of chemometrics. Chemom. Intell. Lab. Syst. 58 (2), 109–130. Elsevier. https://doi.org/10.1016/S0169-7439(01)00155-1.
Wondzell, S.M., Gooseff, M.N., 2013. 9.13 Geomorphic controls on hyporheic exchange across scales: watersheds to particles. In: Treatise on Geomorphology, pp. 203–218. https://doi.org/10.1016/B978-0-12-374739-6.00238-4. Elsevier.